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ACUTE ARTERIAL INJURIES

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Acute injuries of major arteries have long constituted an important and serious problem because they literally threaten both life and limb and because no completely satisfactory solution to the problem has been evolved. Ideally, the objective of therapy is the control of hemorrhage and the preservation or restitution of vascular function. Essentially this means the restoration of blood flow directly through the original channel. Although under certain circumstances the viability of the part may be maintained by the secondary or collateral circulation only, the ultimate functional result in such instances is often far from satisfactory with manifestations of varying degrees of chronic circulatory deficiency. In order to achieve both viability and ultimate normal functional activity it is essential in most instances of injuries to major arteries to restore the continuity of circulation through the original channels. As emphasized previously,[10] however, the attainment of this desideratum is often restricted by certain factors that either jeopardize the effects of ideal therapy or preclude its institution. Depending upon the circumstances involved these include such considerations as time-lag, practical technical difficulties, associated injuries, site and type of arterial lesion, and the possible occurrence of infection.

It has long been recognized that the time elapsing between wounding and institution of therapy is a highly important and influential factor in determining the fate of the limb no matter what form of therapy is employed. This is well exemplified by the experience with arterial wounds of the extremities among American battle casualties in World War II which showed that with increasing time-lag there was an almost straight line progression in the incidence of amputation.[10] Although there is some variation in the survival time of different tissues (for example, skin has a longer survival time than muscle) to acute ischemia, there is obviously a limit to this period of ischemia beyond which viability can no longer be maintained or restored. Accurate determinations of the limits of this period in humans have been difficult to establish because of the variables involved, but clinical experience has indicated a general rather arbitrarily set limit of six to eight hours. In well controlled experiments, to which reference is made later, Miller and Welch found that the survival rate in dog's legs following restoration of circulation was 90 per cent for periods

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of ischemia ranging up to six hours, 50 per cent from twelve to eighteen hours and 20 per cent for periods of twenty-four hours or over. There occurred, however, a variable degree of disability of the limb with contracture and atrophy in those animals whose legs survived following periods of ischemia beyond twelve hours.

Associated injuries, whether they are local or remote, may also be significant. Depending upon their extent such injuries locally may further impair or even completely destroy the regional or collateral circulation, and remotely they may require priority of attention as a life-saving matter, thus necessitating postponement of ideal vascular surgery.

Still other factors which play a significant role in affecting both therapy and end result are the site and type of arterial injury. It is well known, for example, that an injury of the popliteal artery is more serious than a similar injury of the brachial, or that an injury located above the profunda branch in both the femoral and brachial arteries has more serious consequences than one located below this branch. For this reason certain vessels have been considered as critical and others as noncritical. Obviously, restorative surgical therapy has greater significance in the former than in the latter. Variations in the type of injury, including laceration with considerable loss of substance, partial or complete severance, contusion and thrombosis, compression and acute spasm, can also influence both therapy and the ultimate result. And of course surgical repair is attended with less difficulty and greater success in a small cleanly incised wound than in a lacerated wound with much loss of substance.

It is thus apparent that the nature and circumstances of the arterial injury may have a vitally significant bearing upon both the type of therapy that may be employed and the ultimate fate of the limb. They serve to illustrate some of the conditions which affect the ultimate result regardless of therapy and some of the difficulties encountered in the solution to this problem. While they must be recognized as factors which often restrict the application of ideal therapy or jeopardize its effects they need not always be accepted as ineluctable. So long as there is a reasonable chance of survival of the part, every effort should be made to apply ideal therapy designed to restore blood flow through the original channel. As will be indicated later, recent investigations and developments provide much encouragement for the more frequent and successful application of this form of therapy.

SURGICAL MANAGEMENT

In early or immediate treatment of arterial injuries certain well established principles essential to successful management must be observed. These principles have been fully discussed previously[15, 19, 37] and require no further elaboration here. It suffices to say that first consideration must be given to the control of hemorrhage and then to the proper resuscitation of the patient. In this connection, because of its significance both in the treatment of the vascular injury as well as in the proper

resuscitation of the patient, it is desirable to emphasize the extent of blood loss which is often considerable.[10] Owing to the reduction in circulating blood volume, there is reduction in the amount of blood flow through the peripheral vessels. As a consequence the circulation of the part distal to the vascular injury may be even further impaired. Prompt restoration of the circulating blood volume and hemoglobin concentration is therefore particularly important under these circumstances.

Ligation.—As observed above, under certain conditions ligation may be the indicated procedure either because of stern necessity or because the injury involves one of the smaller noncritical vessels. In such instances it should not be done by ligation in continuity but by placing nonabsorbable ligatures well above and below the site of injury, with excision of the intervening damaged segment in order to eliminate the dangers of secondary hemorrhage, thrombosis, and vasoconstrictor influences. Ligation at a level to avoid the creation of a blind panch may be theoretically desirable[20, 30, 43] but the deliberate effort to do so may require extensive dissection which might further jeopardize the circulation of the part. If the concomitant vein is also injured, it should be similarly ligated, but if not, it should not be disturbed.

The deliberate ligation of the concomitant vein for the purpose of improving the circulation of the part has been the subject of much controversial discussion since Makins proposed it in World War I. This matter was thoroughly reviewed recently by DeBakey and Simeone who concluded that on the basis of conflicting experimental observations as well as on the basis of both Makins' figures for World War I and the American figures for World War II, the procedure "furnishes no protection whatsoever against the development of gangrene after acute arterial occlusion and ligation in battle casualties." More recently Simeone and his co-workers[49] have shown experimentally that vein ligation, if anything, further impairs the circulation of the part.

Repair.—As emphasized above, the ideal objective of therapy in arterial injury is the restoration of the flow of blood through the original channel. This desideratum has long been realized and the long history of arterial reconstruction and repair reflects the determined efforts that have been made toward its attainment. Excellent historical resumés of these contributions may be found in a number of publications.[18, 21, 35, 36, 53] Fundamentally, the principles underlying most of these methods of vascular repair are essentially similar, except possibly for certain refinements in suture material or in prosthetic devices. Depending upon the nature of the injury they consist of direct suture repair, end-to-end anastomosis by suture or prosthetic devices, and the bridging of defects by vascular grafts or prosthetic tubes. No effort will be made here to discuss the advantages and disadvantages of these various methods since this has been repeatedly done elsewhere. Because accumulated experience and recent developments point toward suture repair and vascular grafts as the methods of choice, primary consideration will be given them here.

In arterial injuries in which there is little or no loss of substance,

such as small longitudinal or oblique wounds or incomplete transections, especially of the larger arteries, direct suture repair is usually indicated and may be performed with relative facility. Unfortunately, however, this type of lesion is only occasionally observed. More commonly the injury is of such nature that there is a varying amount of loss of substance which often either precludes approximation or permits it only with so much tension against the suture line that the chances of successful repair are considerably jeopardized. For this reason some means of bridging the defect must often be employed.

Principles of Suture Repair.—The essential principles of suture repair are now well established; they include (1) provisional hemostasis, (2) the use of fine needles and silk, (3) accurate approximation of the intima, (4) gentle handling of tissues and maintaining their moisture, and (5) scrupulous avoidance and control of infection. Provisional hemostasis may be obtained, after exposure and isolation of the injured vessel, by the use of small rubber-shod spring artery clamps or soft rubber tubes placed snugly around the vessel above and below the site of the wound. Careful removal of all traumatized tissue and blood clots with excision of ragged overhanging adventitia to provide clean smooth wound edges is essential. The periodic irrigation of the structures with a 1:1000 solution of heparin in physiologic saline to prevent drying of the tissues and to facilitate the gentle cleansing of the wound and lumen of the vessel is also important. The arterial suture should consist of fine silk (5–0 or 6–0) directly attached to a fine curved needle and is available commercially in sealed tubes containing liquid petrolatum.

Various suture technics have been used to approximate the wound edges. They may be classified into two broad categories: (1) plain through-and-through sutures approximating the opposed edges while they are held in an everted position by traction sutures, and (2) the mattress suture placed so as to fix the intima in an everted position. Both of these methods may be modified to the extent of making them either interrupted or continuous. An effort to determine the comparative merits of these various methods was recently made by Shumacker and Lowenberg using controlled animal experiments. These investigators found that the mattress suture provides somewhat superior results to the plain suture with little or no difference between their employment as interrupted or continuous sutures. It would appear, therefore, both on the basis of these studies and clinical experience that the mattress stuture, because it provides accurate intima-to-intima approximation and fixation of the opposed ends of the vessel, is a reliable and satisfactory method. Its use as a continuous or interrupted suture is perhaps best determined by the facility of application under different circumstances. The sutures should be placed fairly close together, about 1 mm. apart. Slight leakage may be observed following completion of the repair and removal of the hemostatic clamp. This is usually readily controlled by maintaining gentle pressure with moist gauze over the

suture line for a few minutes. Occasionally this proves ineffective and additional reinforcing sutures may be required.

These principles of the suture method of repair as applied to end-to-end anastomosis are essentially similar to those developed approximately a half a century ago by a number of investigators.[6, 7, 13, 22] The cut ends of the vessel are brought in apposition and three stay sutures are introduced through all layers of the vessel at equidistant points of the circumference and are tied, care being taken to evert the edges and to provide intimal apposition. Gentle traction upon these stay sutures converts the contour of the arterial ends into straight triangular surfaces which facilitates the performance of the suture anastomosis. Each side of the triangle is sutured consecutively, care being taken to provide accurate apposition of the intima and eversion of the edges. If a continuous suture is employed the running suture is tied to the guy stitch as each segment of the angle is completed.

Vascular Grafts.—In order to permit restoration of vascular function in cases in which the injury is associated with such extensive loss of substance as to preclude direct anastomosis some means of bridging the gap is necessary. A number of methods have been described for this purpose including vascular grafts and prosthetic tubes using suture and nonsuture technics with both intra- and extra-vasal aids or supporting appliances.[4, 23, 31, 42, 51] In light of recent experience it would appear that vascular graft by suture anastomosis as described above is the most reliable method. Autografts or homografts of either veins or arteries have been described and used for this purpose.

In humans arterial autograft may be considered impractical except in unusual circumstances for it has the obvious disadvantage of endangering the circulation of the "donor" area. For this reason *venous autografts* have been usually employed. In using vein grafts it is desirable to employ a segment without valves, or, if valves are present, to place the vein between the ends of the artery with the valves facing distally. In order to avoid either tension or kinking, the vein segment should be of the exact length required to bridge the gap. Another technical consideration is that every branch, even the smallest, of the vein segment must be carefully ligated in order to prevent hemorrhage after the vein is subjected to arterial pressure.

Despite some success in the use of venous grafts, they have not proved entirely satisfactory either in their technical application or their functional performance owing in large measure to the inherent difference in the structure of arteries and veins.[1, 32, 48, 50] For this reason and because of the obvious disadvantages of using autogenous artery grafts, efforts have been made to employ *arterial homografts*. Recent investigations directed along these lines by Gross and his co-workers[17] and by Miller and Welch have produced highly encouraging results. Using aortic segments removed from donor dogs and stored in flasks containing an electrolyte solution, 1 per cent glucose, 10 per cent dog serum, and penicillin and streptomycin (50 units per cc.), and main-

tained in the icebox at a temperature of 1° to 4° C., Gross and his associates found that these vessels remain viable, according to tissue culture studies, for as long as thirty five to forty days.[42a] These segments were then used as grafts in recipient dogs in twenty four animals with no deaths from dehiscence or thrombosis. It was also determined that the grafts carried blood for periods as long as ten months. A similar procedure was used in twelve patients. In nine of these patients it was done to establish an aortopulmonary artery shunt, and in three, segments of preserved human aorta were used in the correction of coarctation of the aorta. There were no deaths in the latter group and only two in the former, and in both of these autopsy showed the grafts to be patent. At the time these observations were reported the grafts had been in place only several months but were found functionally active during that period.

Similar studies on preserved arterial homografts in dogs were done by Miller and Welch. Using a modification of the Halsted-Reichert leg transection replantation procedure they were able first to produce a standard method for producing arterial injury and acute ischemia, depriving the extremity of all its blood supply and causing gangrene in 100 per cent of animals. With this standard preparation as a control, blood flow was restored in the femoral artery, at varying periods ranging from one to twenty-four hours following the onset of the ischemia, by means of femoral artery grafts. Three types of grafts were used with equal success—fresh autografts, fresh homografts and preserved homografts. Failure to restore circulation was primarily dependent upon the period of ischemia. No evidence was found that the preserved grafts were more susceptible than fresh grafts to wound complications. These results are particularly impressive in light of the fact that no anticoagulants were employed.

On the basis of these highly encouraging experimental and clinical observations in the use of preserved arterial homografts there is good reason to believe that this may be the best method of repairing arterial injuries in which there is loss of substance, and thus providing complete restoration of vascular function. This work suggests that arterial banks, like blood banks and bone banks, should be entirely feasible and efforts in this direction now seem practical especially in institutions with an active emergency service for traumatic conditions.

Supplemental Measures.—In the effort to improve the chances of success in maintaining viability of the part and restoring circulation following acute vascular injuries there are certain supplemental therapeutic measures that deserve consideration, including particularly anticoagulant therapy and sympathetic block or sympathectomy.

Anticoagulant Therapy.—The use of anticoagulants, heparin and Dicumarol, would appear to be a valuable adjunct in vascular surgery on the basis of experimental and clinical investigations.[24, 40, 41, 46] By this means the extension of thrombosis in the peripheral collateral tributaries or the occurrence of thrombosis after operation at the site of

repair, might seem to be better controlled. Anticoagulant therapy, however, is not entirely without danger, especially in the presence of extensive injury, and its safe application requires close clinical observation and adequate laboratory studies. For this reason, as indicated previously,[10] it was not considered practical in military practice, and even in civilian practice it would have certain limitations.

In an effort to overcome these limitations Donovan, Thomas and Miller have devised and employed experimentally a method which provides local anticoagulant therapy without significant systemic effects. This was done by the intra-arterial administration of heparin (0.25 mg./kg. of body weight in 10 cc. of physiologic saline) just proximal to the anastomosis through a subcutaneous polyethylene side tube. Preliminary observations by this technic suggest that "an adequate local effect may be achieved without prolonging the general clotting time significantly."

This method of regional heparinization has been employed successfully by Freeman[16] in a small series of patients in the treatment of acute arterial injuries for arterial anastomosis and after removal of arterial emboli and thrombi. The solution of heparin (100 mg. to 250 cc. of physiologic saline) was administered intra-arterially just proximal to the site of anastomosis through a segment of polyethylene tubing inserted through a needle into the arterial lumen. This method of regional anticoagulant therapy appears safe and practical and should greatly increase the scope and usefulness of reparative vascular procedures.

Sympathectomy.—The use of sympathetic block or sympathectomy as an additional and useful supplemental measure to improve circulation is based upon the attempt to counteract vasospasm and to produce maximum vasodilatation in the involved extremity. Vasospasm has long been observed as a response to trauma which directly or indirectly affects vascular structures. It varies considerably in nature and extent with severe localized constriction of the major vessel in some instance and more generalized involvement in others. When it affects the larger arteries it has been referred to as traumatic segmentary arterial spasm, "arterial concussion," "segmental vasospasm," "myogenic spasm" and "stupeur d'artére."[9, 14, 27, 39] The exact mechanism of production of this form of vasospasm and especially the role played by the sympathetic nervous system are not entirely clear and no consistently efficacious method of treatment has been found for it.

In a recent consideration of this problem Learmonth described the varied conditions following which spasm may occur and the different forms of therapy that have been employed with inconstant effects. According to Learmonth, spasm may reduce blood flow by (1) affecting the collaterals themselves, (2) reducing the caliber of the main vessel and closing the mouths of collaterals arising from it, and (3) extension to the distal segment of the main artery. Recent investigations by Kinmonth, Simeone and Perlow have thrown additional light upon

the problem of "reflex spasm" in the large arteries. In experiments upon cats and rabbits these investigators made direct observations upon the femoral artery and plethysmographic measurements of the paw following various forms of stimulation. It was found that local segmental spasm in the large arteries could be readily produced by mechanical trauma, irrespective of an intact nerve supply. Their studies failed to reveal evidence of nervous motor control of the large arteries at least in the cat and rabbit.

If it were shown that similar anatomic and physiologic conditions exist in man, then, on the basis of these observations sympathetic block would be of no value in the treatment of this form of localized traumatic arterial spasm. Clinical experience, however, has shown that in some instances a rather dramatic response follows this form of therapy in traumatic vasospasm.[8, 14] For this reason and because the procedure is relatively simple to perform and carries little or no risk, its continued advocacy seems justifiable. Moreover, these experimental observations do not mean that sympathetic block or sympathectomy is of no value in improving the peripheral circulation of the extremity following acute vascular injuries. The rationale of the procedure under these circumstances is the production of maximum vasodilatation by interruption of vasoconstrictor impulses transmitted over sympathetic pathways to the peripheral vascular bed. These vasoconstrictor influences may or may not be excessive but their removal increases the volume of the peripheral vascular bed and thus augments the circulating blood to the part.[11] This has been found, both on the basis of experimental and clinical studies, to be one of the most effective methods of producing maximum increase in the blood supply of the diseased part and is, therefore, a valuable adjunct both in the early treatment of acute arterial injuries and in combating the later effects of ischemia.[2, 3, 5, 11, 26, 28, 29, 32, 34, 44, 45, 52]

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